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Content distribution in VANETs

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ABSTRACT

Advances in vehicular communications technology are making content distribution to vehicles more effective and increasingly more popular. This paper presents state of the art technologies and protocols for content distribution in VANETs. Major challenges are Internet access spectrum scarcity, mobility, connectivity intermittence and scalability. Aspects covered in this paper include: coexistence of WiFi and LTE; application of network coding; protection from pollution attacks; incentive design for cooperation enforcement; QoS support for video streaming applications. Simulation and testbed results are presented to support the findings. Critical issues that will determine future directions in this area are identified and discussed.

1. Introduction and background

Navigation safety has been the main driver of VANETs in the early years. With the improvement of technology and the increase in popularity of mobile phone applications, new interests have emerged that are related to location aware information and entertainment. Among these, content downloading is probably the most important trend. Beside music, movie trailers, games and restaurant menus, there is a proliferation of location-cognizant data such as virtual tours to local attractions or snapshots of nearby resort areas. Downloading of video camera streams from vehicles facing an accident or a road emergency (flood, fire, etc.) also falls in the local content distribution category, albeit for safety rather than entertainment purposes. A mobile user can download content from access points (APs) that connect to the Internet, using a strategy called Wardriving (www.wardriving.com). Unfortunately the traditional client/server type download will not work because the contact time is insufficient. For example, with a WiFi radio range of 300 m, at 45 mph, the contact time is less than 30 s, and the useful download time is even less if one accounts for the overhead required to set up the Internet connection. Moreover, installing access points every 300 m is too costly. Expecting to find friendly open APs within comparable intervals is unrealistic. Unless the driver is willing to stop in front of the AP when he finds it, one must conclude that in practice, multimedia content downloading at vehicular speed from WiFi APs is not feasible. The only solution that will work in a VANET environment is peer-to-peer "file swarming", enabling users far away from the APs to complete their downloads by exchanging pieces with other interested drivers.

The prime example of P2P file swarming is BitTorrent, where a file is segmented into chunks. Peers discover what chunks the neighbors have that they are missing and promptly exchange them to complete the download. One immediate advantage is to reduce the "flash crowds" load on the content provider. The availability of the pieces is increased because of users' cooperation, and the downloading process is expedited. BitTorrent on wireless however will not work directly as it was designed for the Internet. In the Internet overlay a one hop neighbor may be several physical hops away, requiring a major expense of resources (spectrum and energy). Instead of using overlays, it makes more sense to use physical neighbors for the chunk exchange [1,2]. One such P2P scheme is SPAWN, which uses proximity (instead of the conventional rarity measure) for piece selection and was shown to outperform the "rarest first" criterion of Internet schemes.

By extending SPAWN [1], CarTorrent was born. CarTorrent is a BitTorrent-style file swarming protocol applied to the vehicular environment. CarTorrent clients use k-hop limited scope gossiping to disseminate their chunk availability. Gossip messages are propagated up to k hops from the originator. This allows peers to collect information about piece availability as well as local topology. Topology and availability info is used to select the piece to request next. For example, if A and B own a rarest piece that C desires, and A is at a shorter hop distance than B, the query is sent to C.

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CodeTorrent [3] is a further extension of CarTorrent where source and intermediate nodes can encode pieces before sending them out. In CodeTorrent, a peer can decode a file consisting of k chunks as soon as it receives k linearly independent coded chunks. If nodes fail (e.g. when vehicles get off the highway) while still carrying packets of a coded file, the inherent redundancy of network coding allow transparent recovery [4].

CarTorrent and CodeTorrent schemes use gossip (i.e. opportunistic contact among moving vehicles) for content discovery. A more aggressive approach to content discovery was proposed in the recently introduced ICN (Information Centric Network) architecture. ICNs use a routing paradigm very different from conventional MANETs. In conventional MANETs, the preferred routing scheme for small scale MANETs is OLSR (Optimal Link State Routing), a proactive routing protocol that improves scalability by using the Multipoint routers as relays [5]. In VANETs the predominant routing scheme is Geo-Routing, because of its scalability features and it robustness to mobility. The above schemes were designed for "communications" MANETs charged with efficient delivery of data from point A to point B. In VANETs the traditional routing model is becoming inadequate in view of the emerging applications. People and vehicles most often are not interested in routing to a specific node, rather they want to pull data from ANY node that has the content required by the application, for example, traffic intensity in city streets in the case of intelligent transport. In ICN, when a node is interested in "named" content, it issues an Interest Broadcast Packet carrying that name. This packet is flooded in the network (as opposed to be "gossiped" as in CarTorrent) and leaves records (e.g. Interests) in Pending Interest Tables at intermediate nodes. When the content is found by matching the name, it is delivered back to the consumer using the Interests in the intermediate PITs as "breadcrumbs". The content is cached at intermediate nodes to speed up future searches.

In VANET content downloading application, if the vehicle is interested in tapping a multimedia stream it could efficiently and quickly find it using ICN interest packets. Because of this flexibility, there has been major interest recently in ICNs, especially for mobile networks [6]. In the CodeTorrent application, ICN can retrieve content faster than gossiping, for a price, namely: higher line O/H due to flooding. In a later section, the use of ICN for video streaming will be discussed.

This paper revisits the Car and CodeTorrent models in a modern setting where car radios have both WiFi and LTE interfaces. In this case, reliance on only one or the other interface is not effective, especially for real time multimedia content download. For example, the simultaneous download of a soccer game by thousands of vehicles from the same cellular repeater will lead to congestion and blocking. A WiFi only solution, on the other hand, inevitably fails with sparse users and APs. Thus, synergy between the two schemes is highly desirable. However, the seamless integration of the two technologies can still present challenges. To resolve these challenges, several issues must be addressed such as: (a) identification of parameters that affect WiFi and LTE efficiency in terms of download latency and scalability (e.g. sparseness of vehicles, sparseness of WiFi APs, file popularity, etc.); (b) integration of LTE and WiFi P2P download streams; (c) QoS vs cost trade-offs in the use of LTE vs free WiFi; (d) caching strategies. Moreover, testbed experiments are necessary to study the robustness of the proposed V2X multimedia streaming/retrieval solutions for various applications such as vehicular infotainment and edutainment file sharing.

The rest of the paper is organized as follows. In Section 2, we discuss the challenges and issues that associate with content downloading and peer-to-peer sharing in vehicular networks, and a classification of existing solutions for each challenge or issues. Section 3 revisits the details of CarTorrent, the first and essential content distribution protocol for vehicular networks, and presents the experiment results from implementing CarTorrent on a real testbed. Here we also discuss the unsolved issues with the very basic CarTorrent with only WiFi AP considered. In Section 4, we comprehensively discuss the use of network coding to improve the performance, prove the effectiveness with experiment results, and points out the security and privacy issues that make the network coding vulnerable to attacks. We present existing work on secure network coding and points out the high computational cost of deploying secure coding, thus cause misbehavior of selfish nodes. Hence we present a game theoretic approach of incentive design to enforce the selfish intermediate forwarders to deploy secure network coding for its own long-term benefit. Sections 5 and 6 present a novel architecture for vehicular content downloading and distribution: LTE cluster-based downloading. For this architecture, an incentive compatible scheduling scheme is proposed to enforce selfish vehicles to take the duty of being the cluster head and download original data via costly LTE connection. In order to improve the quality of service for multimedia streaming, we propose a novel two-stage queue deployed at the cluster head to combine both differentiated dropping and network coding. Related work and future directions are discussed in Section 7. Section 8 concludes the paper.

2. Content distribution with VANET Torrent

The VANET architecture examined in this paper runs BitTorrent type P2P file sharing protocols exploiting both WiFi unlicensed channels and cellular LTE channels. In the near future, every vehicle will be equipped with wireless connectivity devices that enable communications with both WiFi and LTE radios. Here, we evaluate the opportunities and challenges of this synergy which we refer to as VANET Torrent or V-Torrent. Initially, VANET deployment was targeted mainly to navigation safety requirements (e.g. VANET was used to deliver "electronic brake lights" to vehicles hundreds of meters back). However, emerging VANETs will exploit high speed WiFi, DSRC and LTE channels to deliver a broader gamut of applications ranging from office-on-wheels to entertainment, P2P file sharing, etc. The focus of this study is on real time, popular media downloading, for example, a soccer game that originates in the Internet. However, the same technology can be used to propagate "emergency awareness" video that originates from other vehicles on the road (e.g. the scene of an accident or a major traffic lockup taken a few blocks away).

Let us first address the new problems that arise when content is downloaded from LTE instead of from the WiFi access point. The first observation is that LTE is a point to point dedicated channel and follows the car as it is moving. In contrast, a connection to the WiFi AP is short lived, several seconds at best. This suggests that, while the download from the AP will be done with UDP, the download from the LTE network can use TCP in order to achieve better performance. Naturally, the LTE connection can itself be noisy and lossy, causing problems with TCP window mechanism. A possible solution is to use network coding to strengthen the connection (via adaptive redundancy) and make it more robust to losses [7].

The second issue that arises is the fact that the LTE spectrum is expensive and it is limited. So, instead of having all the mobiles that are out of WiFi AP range dial up the LTE channel for download (as secure recipe for service collapse!) only a few mobiles connect. The neighbors download from the primary LTE downloaders using P2P. This brings up the issue of identifying the "volunteers" that can best serve as LTE gateways towards the cellular network. This problem is similar to the clustering problem and it can be approached using distributed clustering (as discussed below).

The third issue is the LTE connection cost, as opposed to the low or no cost of the WiFi channel. Mobiles will be reluctant to volunteer for the job, and will try to get a free ride. This problem is similar to the BitTorrent free riding problem. It can be solved as the BitTorrent case was, by using reputation and locking out the free loaders. As for the neighbors that are willing to share the LTE cost, a schedule can be arranged for cars to take turns as LTE gateways. Motion prediction will help maintain good performance through the LTE channel handoff – it behooves to hand off to a vehicle going in the same direction.

In an area where a WiFi connection (either direct from the AP or indirect via multi-hop) is not available, LTE is the only choice. LTE may be the predominant choice in areas served by WiFi if the WiFi channel is overloaded (by residential users, say) and is experiencing delays that degrade the real time application. It is possible to have both LTE and WiFi Internet feeds in an area, and the stream service customer may download in parallel from both feeds. It may also be possible that the LTE channel suffers a bursty loss because of obstacles. It will then behoove the LTE downloader to connect to WiFi as well and receive both feeds, possibly powered by network coding.

There are also security and privacy issues that influence the downloading choice. The LTE channel is better protected from eavesdropping and attacks. Privacy sensitive downloaders will prefer LTE over P2P WiFi. There is also the energy issue, which suggests that LTE will be more energy consuming if the signal comes from a remote tower. Things may change with LTE femtocells. The problem of lowest energy download strategy in a mixed WiFi and LTE environment is a well posed problem that deserves attention, especially since the cellular network was found to be one of the major energy sinks in the urban grid.

So far we have assumed that the video stream comes from the Internet (say soccer game, news reports, etc.). However, in many cases the video comes from another vehicle. For instance, it may be a video that reports on an accident or an emergency, say fire, flood, etc. Suppose the vehicle facing an accident makes its video sharable. Upcoming vehicles upon learning about the accident from safety beacons may submit requests to download the video. Multiple receivers can progressively connect to share the video forming a multicast download tree. If the vehicle population is sparse and connectivity intermittent, the video can be propagated to moving vehicles in a carry-and-forward (delay tolerant) mode. With LTE on board, an emergency vehicle could also transmit the video feed via LTE to a fixed station that makes it available on the Internet.

Next, we complete the picture by considering the remaining aspects that challenge the V-Torrent design. First, mobility and channel propagation can disrupt connectivity and must be seriously accounted for by using proper protection, for example network coding. On the positive side, V-Torrent P2P exchanges are strictly opportunistic exchanges between neighbors. There is no need to maintain multi-hop paths that are vulnerable and unstable in vehicular scenarios. Vehicle density is an important parameter. High density generally favors P2P exchanges and thus is a friend of V-Torrent. Uncooperative nodes are always a problem in cooperative networks like V-Torrent. The common solution is reputation based reward/punishment (as we shall discuss later).

Finally, there is an issue about being able to "get the content" we want. Data exchange is restricted among logical peers, which are actually the physical neighbors. Yet we expect the data to be propagated through the overlay network of peers with a common interest. Even though some peers are found, there is no guarantee that those peers possess useful data. The two main mechanisms that make P2P swarming work are "random" mobility and network coding. The former assists in data propagation. The latter mitigates the "last coupon" problem [3]. With these two mechanisms there is enough opportunistic connectivity among peers, at low cost, so that files can be downloaded in times comparable with other more sophisticated architectures. The ability to connect to LTE and also the introduction of Content Based Routing (associated with the ICN mode of operation) offer V-Torrent a "back door" to content in case the P2P gossip style propagation is too slow.

3. Content pulling from WiFi access points – CarTorrent

3.1. CarTorrent

The original CarTorrent method is based on content discovery via "gossiping". A new car upon entering the highway requests the next AP in range for a specific file name. The AP feeds the car with multiple chunks from that file. It also provides the requester with the number of recent requests for the same file. This is an indication of file popularity and cooperative download opportunity. Vehicles generate gossip messages from time to time to advertise vehicle presence and content. A naive gossiping scheme has a potential of generating a large number of gossip messages as well as ping-pong messages, where two peers keep exchanging stale data. Our implementation sends gossip packets on spanning trees like Minimum Connected Set forwarding, Passive Clustering or Multi-Point Relay, i.e. only the "essential" set of neighbors is asked to forward the data/control packet for a specified number of hops.

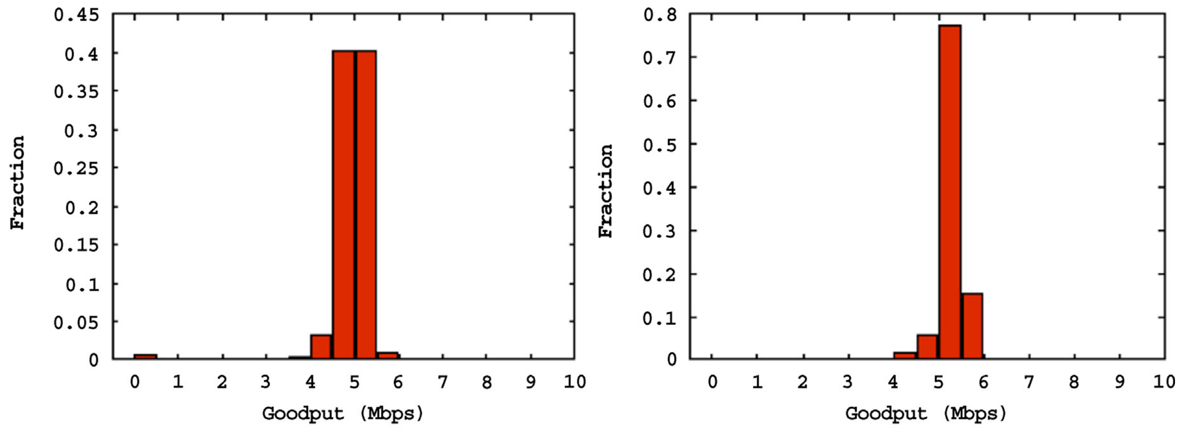
The newcomer, say node A, forwards a gossip control packet with the list of chunks it needs. Selected intermediate nodes participate in forwarding. The first peer, say node B (a few hops away) responds to gossip with the first requested chunk. It also piggybacks its own current list. When A receives the first chunk it requested, it responds by transmitting the first chunk B needs (if any), and so on until B has received all the chunks it can possibly get from A. Basically, this is a "send/wait" protocol between A and B that is concluded when B has received all it needed from A or vice versa. Since we use UDP transport and broadcast MAC, there is no feedback to alert when the system becomes congested. To avoid congestion, rate control can be used. We refer the interested reader to a more detailed paper [8].

Gossiping has various advantages. It works well in intermittently connected VANETs, where the content is propagated hop by hop across subsets of nodes that opportunistically meet each other until it is eventually delivered to the intended destination. Gossiping can introduce large delays that are acceptable only if the application is "delay tolerant", for example, the distribution of the daily paper to travelers. These delays would not be tolerable in a real time broadcast such as a soccer match.

V-Torrent can overcome CarTorrent intermittent WiFi connectivity by leveraging the LTE channel. More precisely, if a vehicle wants to download the soccer video stream it first tries to connect to an AP. If the AP is not in sight, it connects to neighbor vehicles. If none of the neighbor vehicles has a connection to a live soccer stream, the vehicle can get the stream directly from LTE. The path with the lowest delay, and often lowest cost, to the video stream is discovered using ICN in any of the known implementations: Content Centric Networking, Named Data Networking [9], etc. ICN floods interest packets into the VANET, specifying an interest for a particular content, say a World Cup soccer stream. When a node that receives that stream is reached by an interest packet, the stream is propagated also down the path traced by the interest packets (i.e. "backward learning" or "breadcrumb forwarding"). Rate control is enforced in NDN by limiting the interest packet window. If the stream cannot be reached via P2P WiFi connectivity, there is always a back up path via LTE to the content source in the Internet.

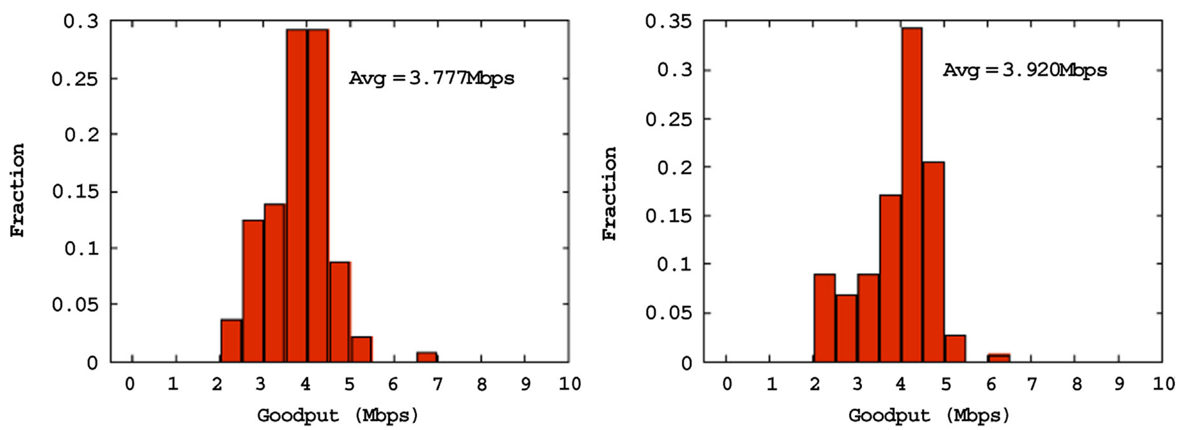
3.2. CarTorrent experiments

In this section we report on a set of earlier experiments aimed at proving the feasibility of in-vehicle content sharing (i.e. CarTorrent) [8].



(a) 64 KB (b) 128 KB

Fig. 1. Parking lot: goodput results.



(a) 64 KB (b) 128 KB

Fig. 2. Moving scenario (vehicles move on a straight road): goodput results.

Toward this goal we implemented CarTorrent and measured its performance in a real VANET testbed. This deployment of a peer-to-peer application on a real VANET testbed was the first of its kind. We showed that peers can utilize the gossip mechanism to recognize one another's presence and employ the piece selection strategy to optimally download files from one another. We ran extensive field tests and obtained performance measurements in a real VANET testbed. We demonstrated performance comparisons between a baseline "static" parking lot case and a mobile "on the road" experiment.

In the first scenario (the static parking lot scenario), two laptops in two parked cars share their files. In the second scenario (the mobile scenario), two vehicles download pieces from each other and from the AP while moving along a road. Each vehicle's laptop has two 802.11b wireless interface cards for V2V and V2I communications. In the moving scenario, upon approaching the AP, the vehicle receives gossips from and at the same time send requests to the AP. The AP responds with the requested pieces. The vehicle also receives gossips and requests pieces from its peers. The request packets carry the information of their originator, allowing the data holder to respond by sending the data out of the correct interface to the intended destination. To avoid interference the two cards are set to channel 1 and 11 respectively. TCP is used for transport and AODV for routing. The interference free underground parking scenario featured a file transfer of 25 MB with piece sizes 64 KB, 128 KB and 256 KB, respectively. The experiment was repeated with two cars on a 1 KM stretch of road. The two vehicles started from both ends with the AP in the middle.

3.2.1. Parking lot scenario

Fig. 1 shows the average piece goodput for piece sizes of 64 KB and 128 KB. Due to TCP window mechanism start up latency, the pieces of larger sizes fare better in terms of throughput. However, once started, for bigger pieces the average per-piece goodput tends to decrease as they are more likely to be lost (due to link errors) and thus must be retransmitted. Moreover, due to buffer size restrictions, larger pieces are subject to fragmentation and more processing. When all is accounted, the lesson of this experiment is that there are diminishing returns when increasing per-piece size.

3.2.2. Moving scenario

In the moving scenario the trend is the same as for the stationary scenario above. Fig. 2 shows the mean per-piece goodput for both peers. As expected the goodput is lower (in this case about 1.5 Mbps less) than the baseline in the parking lot since now there is significant interference from other wireless signals.

4. Use of network coding to improve performance

As per an earlier discussion, network coding finds two applications in the V-Torrent architecture: protection of the multicast stream originating from a source in the Internet or VANET, and protection of the unicast LTE connection from Internet to mobile.

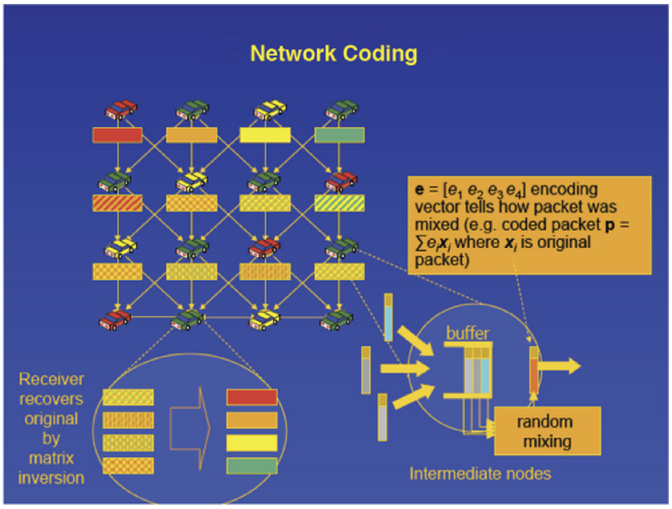


Fig. 3. Random Linear Network Coding in CodeTorrent. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

The LTE connection is typically operated with TCP to improve reliability. However, even TCP fails in high mobility and error rates. We will show how network coding can "clean up" the lower layers giving to TCP a sufficiently reliable network layer for video streaming. In this task we wish to tune the Random Linear Network Coding protocol that is packaged with V-Torrent so that it performs well for both TCP and multicast scenarios. A brief review of Linear Network Coding operation is offered below.

Consider a CodeTorrent scenario (Fig. 3) where the green vehicle at the bottom has submitted a query for packets of the file it is assembling. Suppose next that all the top nodes, driving at the front of the platoon, have received the query and transmit coded packets that span the range of interest of the green vehicle. Generation size is 4. Packets are transmitted hop by hop and are further encoded at each intermediate stage. The green vehicle receives and verifies the packets for linear independence and for compliance with its expressed interest. Upon collecting four independent packets, it arranges them in a linear system of equations and solves it to recover the original generation.

One of the major advantages of network coding is the elimination of the "coupon collection problem" that bugs conventional CarTorrent. This feature is illustrated in Fig. 4 where the download time distributions of CarTorrent and CodeTorrent are compared. In this scenario 200 vehicles are moving in a 2.4×2.4 mile urban scenario following a random motion model (random waypoint). We notice that in CarTorrent the last coupon problem delays some downloads for almost 1400 s, seven times longer than the worst case of CodeTorrent download, measured at 200 s! Moreover, average CarTorrent download is 400 s, four times longer than CodeTorrent.

4.1. Preventing pollution in network coding

Network coding is designed to improve network performance, however, it opens a new source of vulnerability in network communications, namely pollution attacks. A malicious node can compromise some of the encoded blocks and inject them into the network; even a single invalid block can subvert the reconstruction of the original generation and severely affect performance. In order to prevent the attacks, several secure network coding mechanisms have been proposed [10–13]. A secure network coding scheme is a scheme that provides intermediate nodes with a method to verify the validity of coded vectors. Secure network coding schemes based on cryptography have been investigated exploiting homomorphic signatures and homomorphic hash functions [10–13]. These schemes compute a signature (or hash value) while the block is network encoded, and provide a method to verify the validity of the signature of an incoming block. In practice, the homomorphic signature scheme for network coding allows nodes to verify the signature of coded blocks without requiring access to private keys [12]. Zhao et al. introduce a coded block authentication method by computing orthogonal vectors of each coded block [14]. Gennaro et al. propose an RSA based homomorphic signature scheme and a homomorphic hashing scheme for network coding over integers [10].

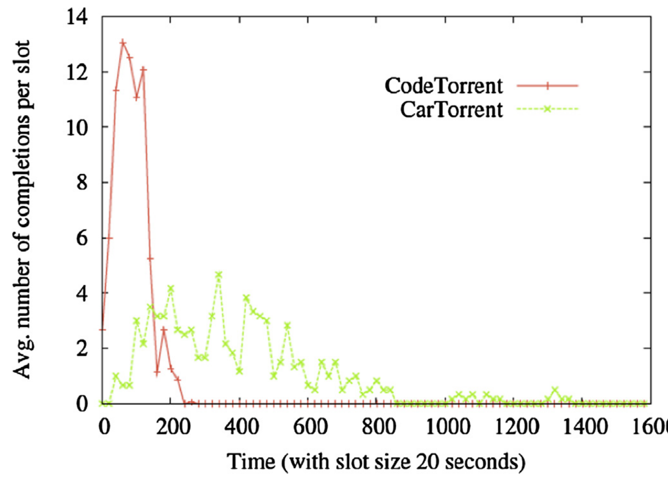


Fig. 4. Comparison of downloading time between CarTorrent and CodeTorrent.

4.2. Secure Coding Incentives – a game theoretical approach

While the throughput of mobile ad hoc networks can be significantly improved by using network coding, network coding in turn implies extra work for forwarders. Selfish forwarders will simply forward packets without coding them in order to avoid the processing overhead introduced by network coding. This is especially true in secure network coding where homomorphic signatures require orders of magnitude extra processing work.

To drive selfish nodes to cooperate and encode the packets, we have explored "social norm" based incentives [15]. Here we review the key results. More precisely we propose a social norm based packet forwarding protocol that enforces selfish drivers to perform secure network coding for their own long-term benefit. The social norm is defined in the context of the distributed game played by the peers. It consists of a social strategy and a reputation system with reward and punishment connected with node behavior. Packet coding and forwarding are the actions of the repeated alternate NC (network coding) forwarding game, and the number of packets delivered determines the payoff associated with each action. As shown in Table 1, there are two players for a one-shot NC forwarding game: the intermediate node R (the selfish forwarder) and the source–destination pair. Node R can choose to perform: secure network coding and forwarding (NCF); simple forwarding without network coding (F) or; total packet drop (Drop). The option of coding without homomorphic signatures is not considered as it is not secure. The S–D pair receives a benefit of B for delivering each packet, and the relay node R has a cost of c_1 for encoding each packet and c_2 for forwarding each packet. Here p is the packet loss rate on the lossy link between R and D.

Obviously the one-shot NC forwarding game has Nash Equilibrium of "Drop", i.e. the intermediate node R will choose to drop the packet to avoid cost, since it has nothing to gain in forwarding others' packets, careless about the benefit of others. However

Table 1
The utility matrix of one-shot NC forwarding game.

	Intermediate node R		
	NCF	F	Drop
S–D pair	$B, -(c_1+c_2)/(1-p)$	$B(1-p), -c_2$	0, 0

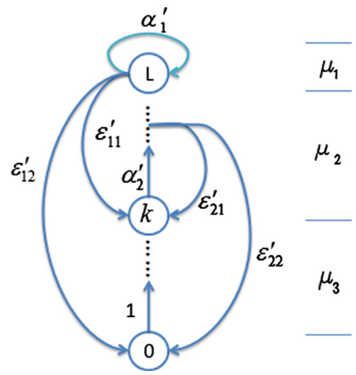


Fig. 5. Multi-stage punishment reputation scheme τ.

when the game is repeated, and the role of relay and sender/receiver is alternated among nodes (i.e. the current relay will become a sender/receiver in the future), the relay node will possibly perform NCF if appropriate incentive scheme is applied.

The social norm incentive scheme is based on a reputation system where every node is tagged with a reputation value θ that represents its historical behavior, and the reputation is propagated periodically among neighborhood. The reputation is an integer between 0 and L. We set a reputation threshold k to divide the reputation interval into three parts: $[0,k-1],[k,L-1],[L]$ indicating low, medium and high reputation respectively. A social strategy σ_0 is proposed as follows: if the source–destination pair has a high/medium/low reputation, relay node serves it with NCF/SF/Drop accordingly. The relay node can choose to obey or not. If it chooses not to obey, its reputation is decreased according to the multi-stage punishment rule, i.e. if it performed "Drop" when the social strategy prescribes "NCF" or "SF", its reputation is decreased to 0; if it performs "SF" when the social strategy prescribes "NCF", its reputation is decreased to k. Fig. 5 shows the state-transition diagram and the probability parameters between each state. Here μ_1, μ_2, μ_3 represent the proportion of nodes with high, medium, low reputation.

Based on the proposed social norm incentive scheme, we proposed an iterative algorithm to compute the steady state of reputation distribution $\eta(\theta)$.

$$\eta^{t+1}(\theta)=\begin{cases}\alpha_1\eta^t(L)+\alpha_2\eta^t(L-1)+1-\delta, & \theta=L\\ \alpha_2\eta^t(\theta-1), & k<\theta<L\\ \delta\eta^t(k-1)+\varepsilon_{11}\eta^t(L), & \theta=k\\ \delta\eta^t(\theta-1), & 0<\theta<k\\ \varepsilon_{12}\eta^t(L)+\varepsilon_2\mu_2, & \theta=0\end{cases} \tag{1}$$

We formalize the problem of finding the optimal social norm parameter settings as an optimization problem with constraints: we aim to maximize the average utility of all nodes (U) subject to the compliance/sustainability conditions (i.e. the long-term utility of complying is always no smaller than deviating).

maximize:

$$U=\sum_{(\theta_R,\theta_S,\theta_D)\in\Theta^3}\eta(\theta_R,\theta_S,\theta_D)u(\sigma)$$

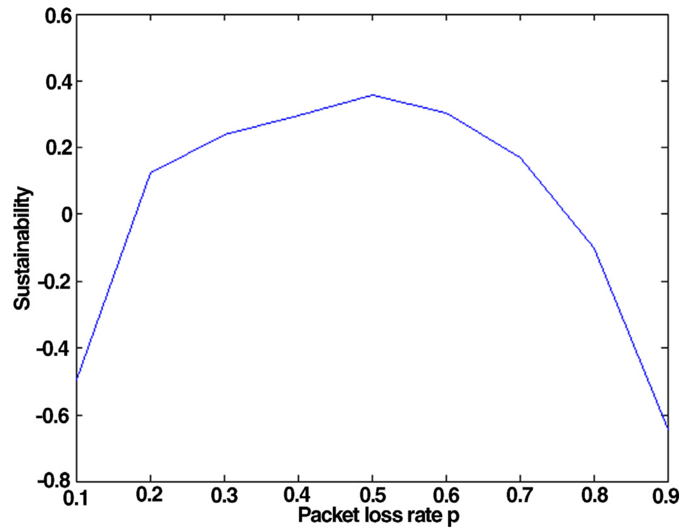


Fig. 6. Enforcement intensity (sustainability) varies after packet loss rate.

subject to:

$\forall\theta\in\Theta$,

$$u^\infty(\theta,\sigma'=\mathrm{F})\leqslant u^\infty(\theta,\sigma_0=\mathrm{NCF})$$
$$u^\infty(\theta,\sigma'=\mathrm{Drop})\leqslant u^\infty(\theta,\sigma_0=\mathrm{NCF})$$
$$u^\infty(\theta,\sigma'=\mathrm{Drop})\leqslant u^\infty(\theta,\sigma_0=\mathrm{F})$$

We proved in [15] that the compliance of the relay node is guaranteed if the persistence factor of the game (i.e. the probability that the relay node will continue its participation of the game) is large enough. And we show the following relationship between the link loss rate and the enforcement (or likelihood of compliance) of the selfish relay node, as shown in Fig. 6.

The social norm game can be directly applied to the V-Torrent system to determine the setting of the parameters that optimize performance. A critical requirement for a fair game is reputation timely and consistent updating (to prevent cheating). We have recently developed a distributed reputation monitoring scheme and plan to test it on V-Torrent.

5. LTE driven clustering

Given the widespread availability of LTE and the possible use of LTE smart phones as vehicle routers, it is appropriate to explore the opportunity of using LTE also for VANET communications. This can have interesting implications on VANET content distribution. In fact, the introduction of the LTE channel changes the download model from a P2P opportunistic strategy (appropriate only for DTN applications) to a more robust, real time supportive content download strategy. New research opportunities arise about the decision to switch from WiFi to LTE when connectivity becomes weak and vice versa.

Consider a vehicle that is receiving a video stream via WiFi. Usually, the vehicle turns to the LTE channel only when WiFi connectivity breaks, e.g. the vehicle ends up in an isolated component. This decision is quite straightforward. However, there are situations when the WiFi connectivity (to content) still exists, but the performance is poor (say, large delays due to congestion near the AP, or transmission errors because of obstacles, or too many hops on path). In such cases, it will be more productive to give up WiFi and set up an LTE connection. The LTE connection, however, comes at a cost. Moreover, if all vehicles independently try to connect to LTE, they may cause an overload on the cell. Thus, if the VANET is dense, it is more advantageous to create a cluster of vehicles

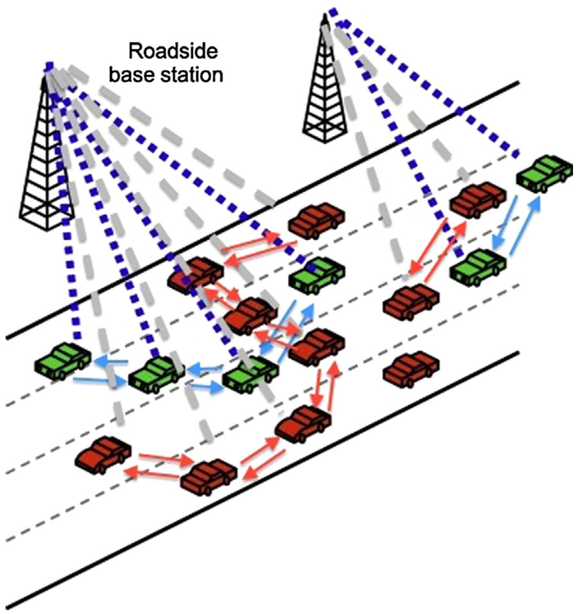


Fig. 7. Cooperative peer-to-peer download scenario within a cluster of vehicles.

interested in connecting to LTE and elect a cluster head that supports the LTE connection and cost. The other cluster members can P2P stream the video from the cluster head. A single user may be reluctant to serve as cluster head for a prolonged period of time because of LTE cost and battery consumption. In this study, we will investigate round robin cluster election schedules so that the costs are evenly allocated among the nodes in the same community. Another approach will be for the content provider to offer compensation and incentives (say free movies) to the volunteer cars.

5.1. Incentive compatible cooperative scheme

We propose a cooperation incentive scheme for content downloading in vehicular networks, where nodes with common interests are incentivized to contribute and download original data chunks from the Internet. Vehicles with the same interests form clusters with one cluster head downloading the content via LTE and share with others, as shown in Fig. 7. The cooperative downloading in a cluster can be modeled as a multi-players' repeated liability game. For this game, we can also apply our social norm based incentive consisting of a social strategy and a reputation system. The social strategy describes the approved actions that nodes should take under different circumstances, and the reputation system monitors and records node behavior in a distributed manner.

Initially, all nodes in a cluster are assigned with a reputation following a uniform distribution over $[K, K+n-1]$ where n is the number of nodes in a cluster. If a node volunteers to be the cluster head and downloads Internet data chunks via LTE and shares with others in this time period, its reputation will increase by $(n-1)$ as reward. Otherwise, if a node does not volunteer (i.e. chooses to be idle) for the last period, its reputation will decrease by 1 as a warning or punishment. If multiple nodes volunteer, the node with the lowest reputation in the group carries the duty, and other volunteers' reputation will keep unchanged for the current period. Usually the node with the lowest reputation is supposed to carry the duty, so if nobody is willing to be the cluster head for the current cycle, the node with the lowest reputation will have a reputation decrease of $(n-1)$. K is a randomly selected integer threshold and it may change over time. All vehicles in a cluster will share their block of content with a neighbor who has a reputation larger or equal to K, and will refuse to share the data with a

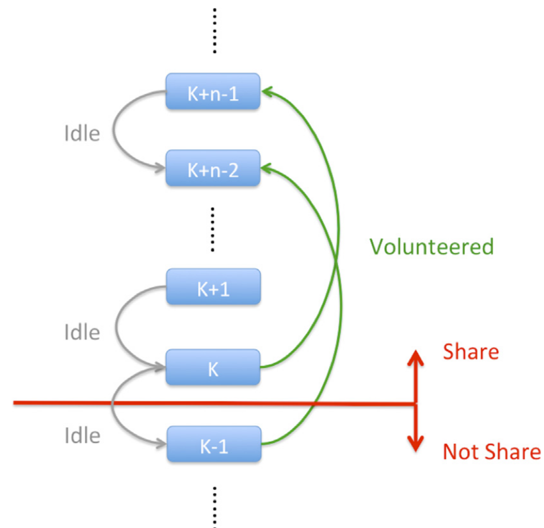


Fig. 8. Reputation update rule for LTE cluster downloading.

neighbor who has a reputation $< K$ as a punishment for not contributing/volunteering. Fig. 8 shows how reputation is updated.

Assume that there's a cost of c for downloading each chunk of data from LTE and a benefit of b for receiving each chunk of data (either directly from LTE or from other vehicle peers). Without the peer-to-peer V-Torrent file sharing scheme, each vehicle would only download for themselves, and has an average utility of $(b-c)$ for downloading each chunk of data. If V-Torrent is applied without incentive scheme, altruistic contributing nodes will have an expected utility of $(b-c/x)$ where x the total number of contributing nodes, and free-rider nodes will have a utility of b; thus selfish nodes would naturally choose to be a free-rider instead of contributor. If V-Torrent is applied with incentive scheme, cooperative nodes will have an expected utility of $(b-c/x)$ where x is the total number of cooperative nodes, whereas free-riders will only have an expected utility of $\lim_{t\to\infty}(b/t)$, which approaches 0 as time goes on; thus selfish nodes would choose to cooperate in order to enjoy the long-term benefit.

5.2. Clustering and LTE downloader selection

Each vehicle constantly compares the "utility of streaming from the AP" (via multi-hop WiFi paths) versus the "utility of streaming from an LTE cluster head" (where the node itself may be the cluster head). Nodes that have chosen the cluster mode participate in a clustering protocol that leads to the election of a certain number of cluster heads and the formation of clusters around the cluster heads. The cluster head role rotates among the members. Several thresholds must be optimized in this clustering process, namely, the weights that allow to trade off the AP streaming utility versus the Cluster Head streaming utility, the depth of the cluster, etc.

6. Adaptive video and congestion control

The VANET may become congested if too many video streams are downloaded from the Internet. This situation is resolved using adaptive video coding. A receiver, upon suffering video packet loss, will shed the video enhancement layers and at the same time it signals the congestion condition to the upstream node. However, the video is generally broadcast among vehicles in a cluster, so it is not scalable to collect feedback information from each and every receiver. Hence, we propose a novel, two level hierarchical video delivery and congestion control architecture. In our system, a video transmission path from the Internet video source to the

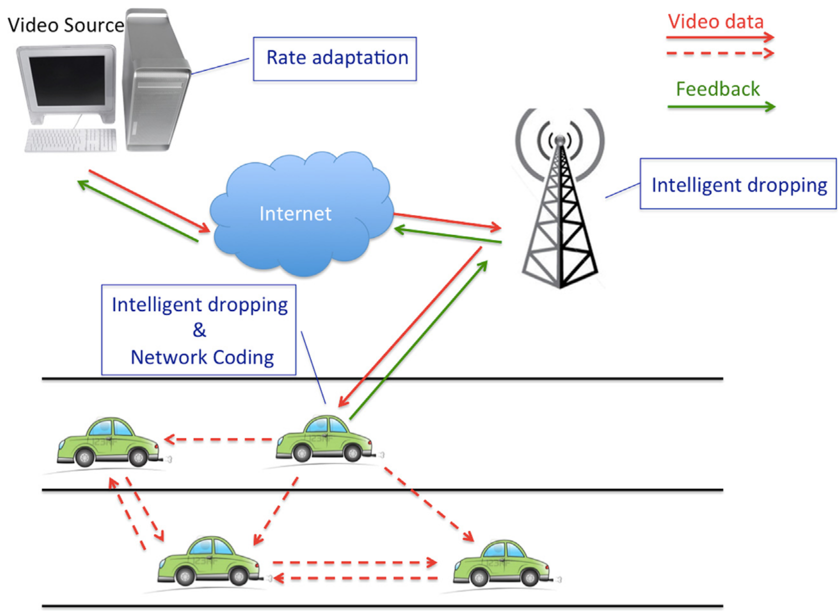


Fig. 9. System architecture for VANET video congestion control.

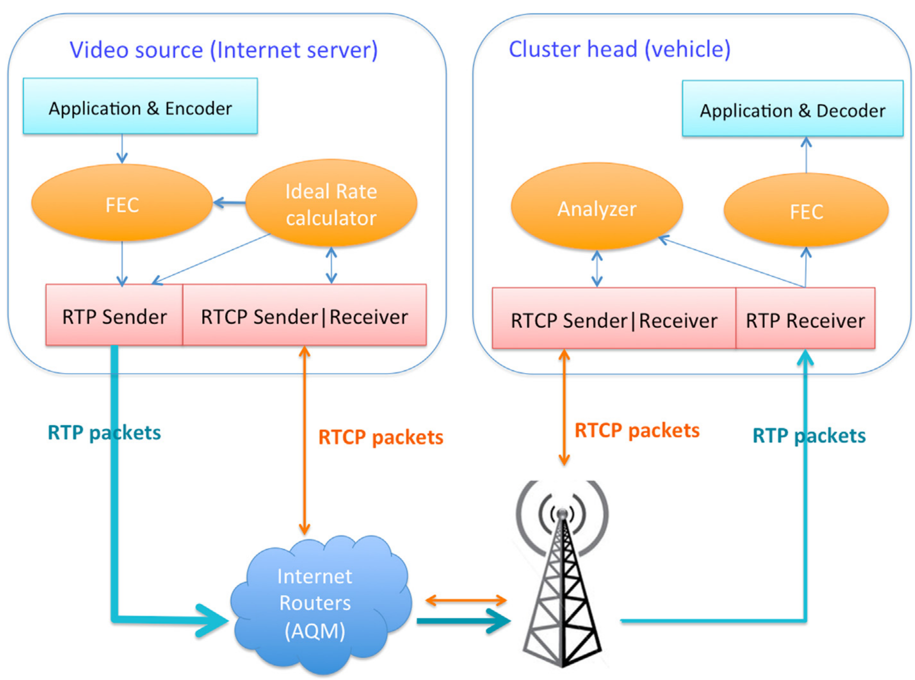


Fig. 10. System architecture of segment 1: unicast from source to cluster head.

vehicle receivers, as shown in Fig. 9, consists of two segments. Segment 1 (the top level) is a unicast RTP session (with feedback flow) from the Internet video source to the cluster head; and segment 2 (at the bottom end of the distribution) is a broadcast UDP session (without feedback flow) from the cluster head to other vehicles in the cluster.

In designing segment 1 congestion control, the vehicle cluster can be viewed as a whole subnet, and the cluster head vehicle as the representative which provides feedback to the source on behalf of the cluster. Traditional point-to-point video congestion control schemes can be directly applied here without specific modification to account for the VANET. Fig. 10 shows the system architecture for segment 1, where video content is encoded and pushed to the Internet as RTP packet stream; routers in the Internet (as well as LTE towers) perform video-based AQM (Active Queue Management) schemes to mitigate congestion and optimize video performance; the cluster head feedbacks the one-way delay and loss rate, etc. to the source as RTCP packet stream; and video source performs rate adaptation according to the feedback information.

In segment 2, i.e. within the vehicle cluster, the cluster head broadcasts the video packets upon request. There is no feedback in this stage to assist in congestion protection. In order to both mitigate congestion and enable the use of Net Coding to cope with the lossy VANET channels, we propose a novel two-stage queue scheme, as shown in Fig. 11. Upon receiving video packets through direct LTE connection, the cluster head pushes the packets to the first queue, the congestion control queue. In this queue video-based AQM (e.g. differentiated dropping) is performed to mitigate congestion based on WiFi channel congestion while at the same

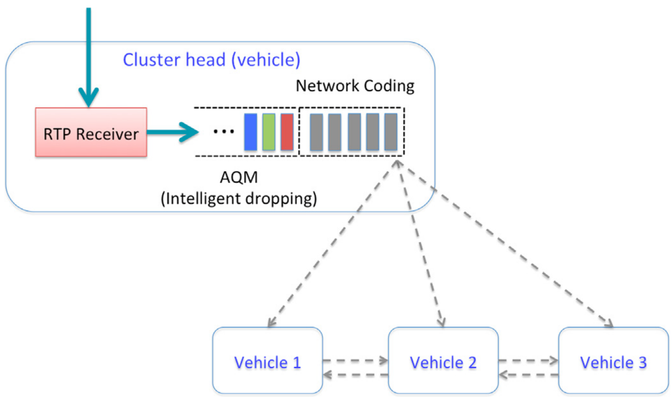


Fig. 11. Segment 2: broadcast from cluster head to other vehicles.

time preserving acceptable video performance. Next, packets are transferred group by group from the front of the first queue to the second buffer. Here packets are network coded generation by generation and are broadcast. No more congestion packet dropping is performed here. Vehicles in the cluster exchange blocks (network coded packets) in a peer-to-peer manner to increase the deliver rate and download speed.

In our system, all video rate adaptation schemes (including conventional equation-based approaches such as TFRC [16,17], as well as LIVA [18], a new scheme relying on explicit congestion signaling from the network to achieve proactive and media-aware congestion control, etc.) and AQM schemes (e.g. WRED, CoDel [19], etc.) at the server can be deployed without modification required by the VANET. Recall that different video packet types have different importance in determining video reception quality. In the MPEG-1 codec, the Intra-frame (I-frame) is more important than the Predicted-frame (P-frame); and P-frame is more important than Bidirectional-frame (B-frame). In scalable video coding (SVC), base-layer (BL) packets are more important than enhancement-layer (EL) packets [20]. The importance of different frames for decoding is reflected in the application of dropping policies. Leveraging this characteristic of SVC, a few proposed congestion control schemes [21–23] deploy intelligent dropping at the router or relay nodes to improve the video performance. Basically, in these schemes, different dropping thresholds are set for different types of frames according to their importance, i.e. dropping less important packets earlier to save more important packets. In VANET, we propose that the cluster head and intermediate vehicles also perform intelligent dropping to improve video quality when congestion happens. Simulation results in [21–23] show that intelligent dropping leads to significant improvements in video QoS/QoE. Note that the dropping must be done in the first queue, before the packets are Network Coded and mixed in the second queue in order not to affect the receiver's ability to reassemble the generation. The careful reader will note that coded packets may still be lost in the VANET during the P2P exchange due to random errors, interference, etc. However, these losses are recovered by redundant transmissions from the coded buffer and also by the intrinsic redundancy of the multipath VANET.

7. Related work and future directions

In this section, we review previous work in the VANET content distribution area, and discuss future research directions.

One of the early contributions to cooperative data retrieval was the system COMBINE by Ananthanarayanan et al. [24]. COMBINE uses multiple radio access technologies and is specifically designed for collaborative downloading. It integrates neighboring nodes' Wireless Wide Area Network (WWAN) inputs to download resources on behalf of an active node. After downloading, the neighboring nodes deliver the data to the active node using WLAN links. Other researches have focused on adaptive video coding as a means to provide good quality video streaming. Leung and Chan proposed a protocol called Collaborative Streaming among Mobiles (COSMOS) using Multiple Description Coding (MDC) in wireless networks [25]. Several mobile users equipped with wireless devices (WiFi, Bluetooth, etc.) form a peer-to-peer network. Some among them have the capability to pull data from the 3 G network. The multiple descriptions are then transmitted to peers. The more descriptions one retrieves, the better the video quality. In [26], the authors proposed Cooperative Video Streaming over Vehicular Networks (CVS-VN) to utilize cellular networks (3 G/3.5 G) and DSRC to achieve better QoS. Multimedia stream is divided into substreams each of which is further divided into base layer (BL) and enhanced layers (ELs). The BL is downloaded directly by the requester from the cellular network to guarantee basic QoS. The ELs are retrieved by neighbor helpers via their cellular network channels and are subsequently transmitted to the requester via DSRC. In another contribution, Fan et al. describe a multiple session joint scheduling (JOSCH) mechanism to deliver layer-encoded streaming over heterogeneous wireless networks [27]. A coordinator server schedules video layers over heterogeneous radio access channels using a skew scheduling algorithm as opposed to the traditional "base layer transmitted first" scheduling.

Other approaches to reliable video streaming in vehicular networks are based on network coding. Uichin Lee et al. describe an efficient scheme to achieve reliable dissemination of emergency videos in VANETs using network coding [28]. Likewise, Mark Johnson et al. investigate the challenging problem of delivering low latency content over a highway environment [29]. The key feature in their approach is the use of multi-hop randomized network coding in order to achieve reliable dissemination of contents in the vehicular network. Razzaq and Mehaoua propose a multi-stream coding mechanism where paths are chosen according to their importance [30]. To improve reliability, some nodes along the transmission path store the received packets for retransmission in case of packet loss.

After reviewing the existing related work and after considering our own contributions, we have prepared a list of research directions that we think will impact future research on VANET content delivery.

- As more content is produced by mobile devices as opposed by Internet Servers, e.g. tourists who take pictures/videos at tourist site and make them available to share with people nearby. For this application, ICN or NDN will become critically important in terms of caching, searching and distributing content among mobiles.
- Given the dilemma that network coding at intermediate forwarders causes pollution issues and must be protected by computational intense homomorphic signatures, cache coding can come to help by removing the need for homomorphic cryptography. With cache coding, the content is cached at the intermediate nodes for future requests, and the intermediate nodes thus become "peers", and have to be responsible for the integrity of the content, because all peers sign when re-encoding the packets. Hence, we believe cache coding will play an important role in future vehicular networks.
- In order to provide suitable quality of service for video stream distributions, cache coding should also be extended to video stream contents where all types of frames (I/P/B) should be cached, and nodes will be able to forward different subsets/combinations of the frames to provide different video quality services according to the channel condition.

- Finally, synergy of multi-homing connection and multi-path routing should definitely be explored to support smooth hand-off and efficient content downloading. This is because when vehicles drive on freeways, the interval between APs needs to be filled up with LTE connection. Hence, content download needs to go through both LTE and WiFi (and multiple WiFi APs), as well as from other vehicles.

8. Conclusion

In this paper we have presented state of the art technologies and protocols for content distribution in VANETs. We have exposed critical issues that impact the throughout performance and have identified future directions. One major positive result was the significant improvement achieved with network coding. The need to protect network coded packets from pollution was also discussed, and the significant processing cost of providing this protection with homomorphic signatures was noted. Proper incentives must be given to drivers to persuade them to go ahead with coding. The effectiveness of LTE downloading was clearly evidenced. The extra LTE cost can be spread out among participants using again some form of incentives. Finally, video streaming was studied with particular attention to errors and packet losses. A novel two-stage queue was proposed to perform congestion control without affecting network coding efficacy.

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